PROCESS OF FORMATION OF A HIGH-QUALITY ENAMEL COATING

A. V. Nikitenko[1]

The force action on the slip layer in the course of formation of an enamel coating on an article performing a complex motion is studied. The forces acting on ann elementary volume of the enamel slip are calculated. The main types of forces fostering removal of excess slip and formation of a uniform coating are identified. The conditions for producing a high-quality enamel layer are considered.

The ability of a technologist to achieve the required degree of reproducibility of properties, for example, in enamel products, depends of the attained level of knowledge of the regularities of the technological process and the possibility of controlling these regularities [1]. The quality of enameling by the moist method is primarily a function of the rheological properties of the enamel slip and the fields of forces developed on the surface of the article in formation of the coating [2, 3]. The reproducibility of the required quality level is determined by the effect, on these properties, of many factors that vary in time. The aggregate effect of such variations can overstep the permissible limits.

Numerous data on the reasons for the variability of the properties of enamel suspensions have been accumulated [4]. Various methods have been proposed for simulating the technological properties of enamel slips for the purpose of obtaining data for their preparation and for control of the properties [5]. Such modeling is especially useful in using enameling machines, where strict requirements on the stability and reliability of the enameling processes are imposed.

It has been established that restoration of the enamel-slip structure occurs 0.88 – 1.80 sec after cessation of disruption [6]. On the one hand, the observed relaxation properties along with the strength parameters determine the ability of a glass-enamel suspension to form a coating with the required thickness. On the other hand, fluctuations in the slip properties, rapid restoration of the slip structure, a complicated geometric shape of the enameled article, and the presence of protruding fittings on the enameled article have an unfavorable effect on the quality of enameling.

An important problem is the creation of automated enameling machines with a kinematics that would allow the development of the required fields of forces on the enameled-article surface. It is possible to expand the level of understanding of the regularities of an important stage in ena-

meling technology by studying the process of slip-coating formation using the scheme presented in Fig. 1. In each specific case, different types of motion are imparted to the article: planetary (at $\alpha = 0$), rotary (with ω_1 and ω_2 having different magnitudes and directions), reciprocating (with a sign-variable ω with a frequency less than 1.5 Hz), swinging (with $\alpha = f(t)$, $\omega_1 = \omega_2 = 0$, $\overline{O_4 O_5} = 0$), vibrational (with a sign-variable ω with a frequency of 10 – 100 Hz), and combinations of them.

Let us consider the set of forces acting on an elementary volume of enamel slip on the surface of some article. Let us assume that rotation takes place around the axes OO_1 and OO_2 with the corresponding velocities ω_1 and ω_2. The origin of the moving coordinate system is selected at the center of the circle O_2, the Z axis coincides with the line OO_2, the
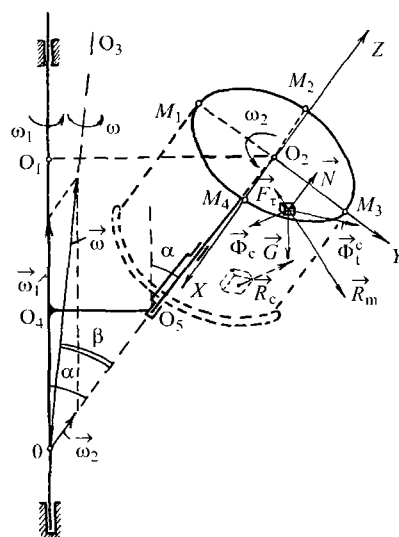

Fig. 1. Distribution of forces in the slip layer in formation of an enamel coating on an article performing a complex motion.

[1] South Russian State Technical University (NPI), Russia.

plane XO_2Y lies in the plane of the circle, the X axis is directed tangent to the trajectory of motion of the center O_2, the Y axis is directed normal to this trajectory, and $\overline{O_4O_5} \neq 0$.

The absolute velocity ω is found from the equation

$$\omega = \sqrt{\omega_1^2 + \omega_2^2 + 2\omega_1\omega_2\cos\alpha} . \tag{1}$$

The angle determining the direction of the vector of the absolute angular velocity and the position of the instantaneous axis of rotation OO_3 is expressed by the formula

$$\beta = \arcsin\left(\frac{\sin(180° - \alpha)\omega_1}{\omega}\right). \tag{2}$$

The motion of the elementary volume simulating a slip particle should obey the basic equation of the dynamics of the relative motion of a point [7]:

$$m\frac{d\vec{v}_r}{dt} = \vec{\Phi}_t + \vec{\Phi}_c + \Sigma\vec{P}_i .$$

where m is the mass of the elementary cell of the enamel slip; $\dfrac{d\vec{v}_r}{dt}$ is the vector of its relative acceleration; $\vec{\Phi}_t$ and $\vec{\Phi}_c$ are the vectors of the transport and Coriolis forces of inertia; $\Sigma\vec{P}_i$ is the geometric sum of the force of gravity $\vec{G}$, the normal reaction of the surface $\vec{N}$, and the force of resistance of the medium $\vec{F}_\tau$.

Since the normal reaction $\vec{N}$ is directed perpendicular to the surface, it has no effect on the relative motion of the slip layer. The force of resistance of the medium $\vec{F}_\tau$ will be evaluated by the limiting dynamic shear stress $\bar{\tau}_0$. The condition determining the start of motion of the elementary slip volume and, accordingly, of the processes of coating formation and removal of excess slip is an excess of the resultant $\vec{R}_m$ of the inertial forces and the force of gravity over the force of resistance of the medium $\vec{F}_\tau$ [8]. This means that the vectors $\vec{R}_m$ and $\vec{F}_\tau$ are oppositely directed.

The transport motion is uniform rotation. Therefore, the transport force of inertia will be expressed only by the centrifugal force

$$\Phi_t = \Phi_t^c = m\,\omega^2 r_i ,$$

where r_i is the distance from the instantaneous axis of rotation OO_3 to the i-th surface point.

The Coriolis force of inertia will be determined as

$$\Phi_c = m \cdot 2\omega v_{r_i}\sin(\hat{\vec{\omega}, \vec{v}_r}).$$

where v_{r_i} is the relative velocity of the elementary slip volume at the i-th surface point.

The direction of the vectors of the inertial forces $\vec{\Phi}_t^c$ and $\vec{\Phi}_c$ is opposite to the direction of the vectors of the corresponding accelerations $\vec{W}_t^c$ and $\vec{W}_c$.

Let us consider the conditions for formation of a coating on the flat bottom surface perpendicular to the axis OO_2. For the four diametrically opposite points M_i, the distance r_i is determined as:

$$r_1 = \overline{OO_2}\sin\beta - \overline{O_2M_1}\cos\beta;$$

$$r_2 = r_4 = \sqrt{(\overline{O_2M_2})^2 + (\overline{OO_2}\sin\beta)^2};$$

$$r_3 = \overline{OO_2}\sin\beta + \overline{O_2M_3}\cos\beta.$$

Let us project the vectors of the forces acting on the elementary slip volume on the X and Y axes:

$$\begin{cases} m\left(\dfrac{dv_r}{dt}\right)_X = m\omega^2 r\cos\varphi_1\cos\varphi_2 + \\ 2m\omega v_r\sin(\hat{\vec{\omega}, \vec{v}_r})\cos\varphi_3\cos\varphi_4 - F_\tau\cos\varphi_5; \\ m\left(\dfrac{dv_r}{dt}\right)_Y = m\omega^2 r\cos\varphi_1\sin\varphi_2 + \\ 2m\omega v_r\sin(\hat{\vec{\omega}, \vec{v}_r})\cos\varphi_3\sin\varphi_4 + G\sin\beta - F_\tau\sin\varphi_5, \end{cases} \tag{3}$$

where φ_1 and φ_3 are the angles of the vectors of the centrifugal and Coriolis forces of inertia to the considered plane; φ_2 and φ_4 are the angles between the X axis and the projections of the indicated forces onto the plane of the circle; $\varphi_5 = f(\Phi_t^c, \Phi_c, G, \varphi_1, \varphi_3, \beta)$ is the angle between the vector of the force of resistance of the medium to the X axis.

Let us set the following specific values for the geometric and kinematic parameters adopted, with certain variations, in the calculations and the design of enameling machines: $\alpha = 20°$, $\omega_1 = 10.5\text{ sec}^{-1}$, $\omega_2 = 1.3\text{ sec}^{-1}$, $\overline{OO_1} = 0.98$, $\overline{OO_2} = 1.1$ m, $\overline{O_2M_i} = 0.1$ m. Their relation is selected in such a way that slip removal is provided by slipping off the article surface.

Substituting these values in formulas (1) and (2), we find the needed parameters: $\omega = 11.7\text{ sec}^{-1}$, $\beta = 17.8°$.

Let us determine the projections of the forces acting on the elementary slip volume ($3.2 \times 10^{-9}\text{ m}^3$) for the outer points of the surface M_1 and M_3. The force of resistance of the medium will be found from the condition that the working value of the limiting dynamic shear stress of prime slip is within the range of $\tau_0 = 9.0 - 12.0$ Pa.

Here we take into account that the initial thickness of the layer of enamel slip is equal to $0.30 \times 10^{-3} - 0.35 \times 10^{-3}$ m [9]. After the end of coating formation, the coating thickness is $0.18 \times 10^{-3} - 0.19 \times 10^{-3}$ m. The density of the working prime slip is $\rho = 1640\text{ kg/m}^3$. Then $F_\tau = (0.9...1.2) \times 10^{-5}$ N.

The weight of the elementary slip volume is $G = 0.5 \times 10^{-5}$ N, and its projections are $G_X = 0$, $G_Y = 0.15 \times 10^{-5}$ N. This means that there will be no spontaneous slip flow in the field of action of just gravitational forces. Let us assume that due to the inertia of the considered system, the layer will start slipping over the surface at a time $t_i = 0.1$ sec after the article starts rotating. It can be assumed with a sufficient degree of accuracy that at the points M_1 and M_3, this will occur along the Y axis. Using system (3), we express the velocity of relative motion v_r at the moment the layer starts moving:

$$v_{r_{1,3}} = \left(\omega^2 r_{1,3} \cos \beta + g \sin \beta - \frac{F_\tau}{m} \right) t_i .$$

Substituting the corresponding values, we determine its specific values at the considered points: $v_{r_1} = 1.55$ m/sec, $v_{r_3} = 4.03$ m/sec.

Let us find the projections of the centrifugal and Coriolis forces of inertia on the X and Y axes:

for the point M_1: $\Phi^c_{tX} = 0$, $\Phi^c_{tY} = 1.658 \times 10^{-5}$ N, $\Phi_{cX} = 1.82 \times 10^{-5}$ N; $\Phi_{cY} = 0$;

for the point M_3: $\Phi^c_{tX} = 0$, $\Phi^c_{tY} = 2.966 \times 10^{-5}$ N, $\Phi_{cX} = 4.74 \times 10^{-5}$ N; $\Phi_{cY} = 0$.

It follows from a comparison of the results obtained that in moving away from the instantaneous axis of rotation OO_3, the projections of the centrifugal and Coriolis forces of inertia will increase. The first projection increases 1.8-fold, and the second 2.6-fold. The force of resistance of the medium is weaker than the centrifugal and Coriolis forces of inertia by a factor of $1.66 - 2.97$ and $1.82 - 4.74$, respectively. Accordingly, the resultant $\bar{R}_m$ of the inertial, gravitational, and resistance forces is determined largely by the inertial forces, and the projections of all resultants of forces on the bottom converge at some point that does not lie on the instantaneous axis of rotation.

The resultant $\bar{R}_{cyl}$ of the forces that form a coating on a cylinder acts in a plane tangent to the cylindrical surface and directed from the rim to the bottom along an inclined plane.

Thus, in the considered complex rotation of the article, the main forces determining the motion of the layer of enamel slip suspension over the surface are the centrifugal and Coriolis forces of inertia.

Since the centrifugal force of inertia depends on the distance to the axis of rotation, the greatest removal of excess slip will occur from sites on the article surface most remote from it, primarily from the fittings. This can result in burnout of enamel on the fitting parts in the course of firing. Removal of excess slip takes place virtually immediately after the article starts rotating. Subsequent force action only molds the slip coating. Unidirectional rotation of the article can lead to the appearance of buildup of enamel in front of the handles. If the article is fixed rim upward in the machine clamp, enamel can also be accumulated under the rim.

Consequently, the use of rotary motions frequently implemented in rotary enameling machines is reliable only when enameling an article of simple geometric shape representing a body of revolution. Therefore, enameled articles ought to be designed separable. As regards to tableware, this means detachable fittings, the combinig of enameled parts with parts made of other materials, etc.

A uniform slip coating on articles of complex geometric configuration can be attained on conveyer machines (for example, the production line made by the Moneta company, Italy). Such machines perform shock-swinging motions with the article fixed in the clamp and create tilts directed to different sides. In such cases fluctuations in the enamel-slip properties have a less perceptible effect on enameling quality.

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